The Southern Border Zones of the OMZ and SNM in the Central Arabian Sea with "Holes" in the SNM

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Introduction

In the open ocean below the permanent pycnocline, the dissolved O_2 content is essentially determined by the shifting balance between supply by (vertical eddy diffusion and horizontal advection) versus consumption. Current eddy-resolving models in the Arabian Sea (e.g., Resplandy et al., 2012) are reasonably correct about the rates and maintenance of vertical and geographic-horizontal O_2 distribution.

They are weak regarding discontinuities in hydrography, e.g., variability in the location of border regions between the major water masses known from field studies, specifically about latitude and horizontal O_2 gradients near 12-14° N, the transition to severe suboxia or anoxia in the OMZ.

Profile from the Arabian Sea OMZ by R/V *Meteor*

(O_2 titration end point by visual detection)

Sta. Date	Depth (m)	Temp. (°C)	Sal.	O_2 (ml L^{-1})	O_2 (µM)	NO_2^- (µM)	NO_3^- (µM)
248	50	25.90	36.22	4.84	215.9	0	0.04
18.1°N, 65.0°E	60	25.53	36.24	4.64	207.3	0.05	0.14
5/15/95	75			3.99	178.2	0.74	3.98
	80	24.89	36.30	3.89	173.7	0.48	5.18
	100	24.37	36.31	0.07	3.1	0.07	8.93
	150	20.41	35.86	0.07	3.1	0.08	22.03
	200	17.51	35.63	0.08	3.4	3.61	17.84
	250	15.81	35.70	0.08	3.4	3.62	15.73
	400	13.62	35.78	0.07	3.0	2.75	18.62
	800	10.65	35.57	0.09	3.8	0.04	28.43
	1200	7.35	35.24	0.34	15.0	0	33.71
	1500	5.44	35.06	0.87	38.8	0.01	34.11

Winkler titration versus NO_2^- Content

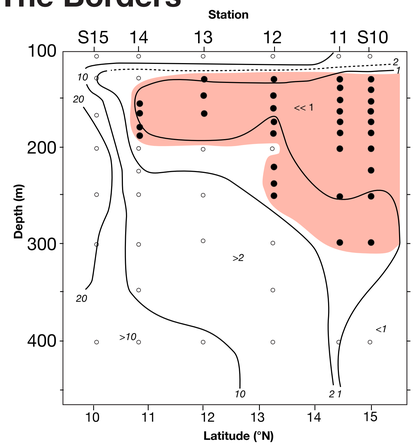
Below the primary NO_2^- maximum near the bottom of the euphotic zone (with high O_2), the colored depths comprise samples with about the same O_2 values reported from titration that are at the lower limit of sensitivity of the procedure. Purple-shaded lines show the high NO_2^- values signifying NO_3^- reduction, which commences at O_2 levels more than one order of magnitude below the lower limit of high-quality Winkler titration (Thamdrup et al., 2012, using the new STOX sensor). These reported O_2 are clearly overestimates.

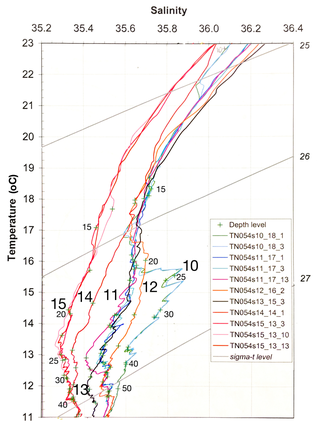
The presence of NO_2^- suggests functional anoxia by resident metazoans. The yellow-shaded O_2 values may or may not be correct.

Concurrent values of >0.5 µM NO_2^- at low O_2 delineating the SNM may serve to eliminate O_2 data from titration until the newer, highly sensitive methods of O_2 measurements are broadly available (besides STOX and optodes, Holtappels et al., 2014).

The same high-NO_2^- check at low O_2 can be applied to historical data for eliminating false O_2 data from titration, back to the 1930s, as well as describing the historical extent of the SNM.

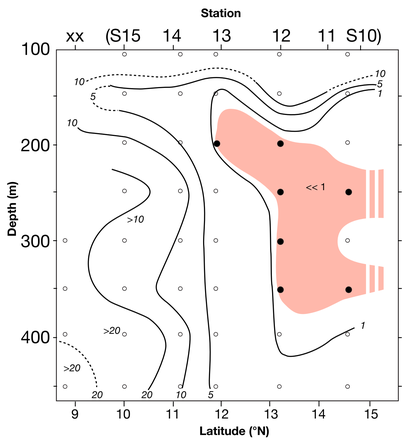
The Borders

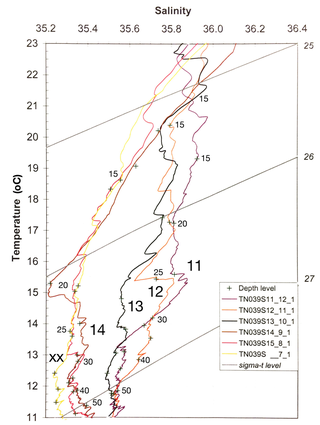




Sections of O_2 (µM) from titration and T-S diagrams along 65°E during December 1994 (left; nearby JGFOS sts. indicated on top) and December 1995 (right).

Isolines for O_2 based on titration. Filled circles denote samples with >0.05 µM of NO_2^-, where the actual O_2 level was very much lower than found by titration (0.05 µM NO_2^-, border of pink colored SNM). The SNM is not accessible by Winkler analysis (Banse et al., 2017).

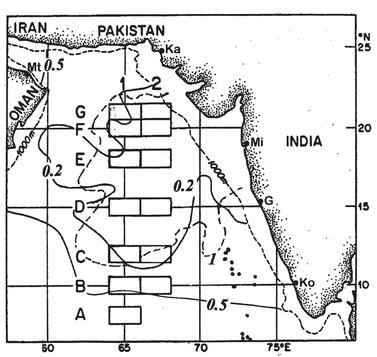




The T-S relations changed to the south of the principal horizontal O_2 gradients, as they did similarly during the other five visits to the section in 1995 by R/V *T.G. Thompson* although the location of the subsurface salinity front shifted by ~1° of latitude. Likewise, during December 1986 along 64°E, the very sharp border zone (O_2 fell from 30-50 to 4-7 µM in ca. 50 km) occurred near 13°N, accompanied by a change of water mass (R/V *Charles Darwin*, cruise 19, section along 64°E).

Key to insets in T-S diagrams: TN050, *Thompson* cruise no.; S11, JGOFS station no. (also on top abscissa of sections); rest, cast identif. - Large Roman digits near lines, station no.; small digits, depth in decameters. Slanted lines, density.

Results: The locations of the OMZ and SNM border zones are determined by hydrography rather than a shifting balance between supply and consumption of O_2.



The boxes (left, "1", right, "2"); full lines, O_2 (mL L-1) at 200 m (Wyrtki, 1971); dashed, approx. SNM outline (NO_2^- =1 µM, Naqvi, 1991). G, Goa; Ka, Karachi; Ko, Mi, Mumbai; Mt, Muscat

Climatology of NO_2^- (1960–2004) in the SNM of the central Arabian Sea with number of aerated "holes"

Box	~200 m 1	~200 m 2	~300 m 1	~300 m 2	~400 m 1	~400 m 2	~500 m 1	~500 m 2
G 21°N	13–21 **1.25**	1–13 **0.56**	11–20 **1.00**	0–14 **2.66**	8–24 **0.17**	0–14 **1.98**	5–23 **0.64**	0–13 **1.29**
F 20°N	19–26 **1.90**	2–7 **1.85**	6–35 **1.71**	0–9 **2.67**	7–31 **1.50**	0–7 **1.44**	12–25 **0.51**	2–3 **1.25**
E 18°N	4–12 **1.40**	2–16 **3.14**	1–14 **2.90**	1–14 **2.73**	1–15 **1.36**	1–16 **1.47**	7–4 **0.14**	8–9 **0.29**
D 15°N	13–21 **3.22**	3–37 **2.93**	9–23 **1.73**	8–30 **1.55**				

The boxes D-G as in the map: ("1") the western and ("2") eastern boxes. The first line counts the observations with ≤ 0.05 µM NO_2^- [in red] and ≥ 0.06 µM NO_2^- [in black], respectively (from Table S1B in Banse et al., 2014). Bold font below, medians (µM NO_2^-) of the second category.

Oxic "holes" in the SNM

Of 650 NO_2^- measurements in the SNM from 1960-2004 between ~200 and ~500 m depth, 154 (23.7%) in red ranged from zero to 0.05 µM NO_2^-. They suggest that some O_2 was still present and so they may not have been functionally anoxic for resident zooplankton.

At a few stations the "holes" with zero to 0.5 µM NO_2^-, but with clear vertical gradients of temperature and mild ones of salinity, are stacked down to 400 or 500 m depths. They might reflect deep-reaching eddies.

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